In-Flight Antenna Characterization of a SAR Instrument Operating in Complex TOPS Mode

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Abstract: *The antenna model used for correcting the influence of the antenna pattern on synthetic aperture radar (SAR) images requires on-ground validation and in-flight verification. A methodology based on the in-flight measurement of azimuth patterns with ground receivers has been successfully performed for the missions TerraSAR-X (TSX) and TanDEM-X (TDX), namely for operational modes and beams. Future satellite missions such as Sentinel-1 will have the novel and complex TOPS (Terrain Observation by Progressive Scans) as operational mode. This paper presents the first in-flight antenna characterization of a SAR instrument in TOPS mode with ground receivers, performed with experimental TSX data. The results demonstrate the suitability of the calibration approach and, extendedly, the accuracy and stability of the TSX antenna model.*

1. Introduction

The calibration concept used for the missions TerraSAR-X (TSX) and Tandem-X (TDX) is based on a precise antenna model [1] and the pseudo-noise (PN) gating method [2]. For both missions the antenna model could be validated on-ground and successfully verified in-flight: in elevation by acquisitions across the Amazon rainforest and in azimuth using ground receivers (GRs). The achieved accuracy was of ±0.2 dB in elevation (2-way pattern) and down to ±0.1 dB in azimuth (1-way pattern) [3].

However, until now the verification of the antenna model has been performed for nominal operation modes and beams, but not for an experimental mode like the complex TOPS mode (Terrain Observation by Progressive Scans) based on multiple steered azimuth beams [4]. In TOPS the antenna is rotated in the opposite direction to the spotlight mode, back to forth, in order to reduce some of the drawbacks observed in ScanSAR operation like scalloping. On the other hand, in electronically steered antennas, the limited number of steps used by the azimuth steering angle quantization produces an amplitude modulation in the antenna gain as seen by a point target [5].

TOPS is an experimental mode for TSX, which is currently the only in-orbit SAR system capable of acquiring TOPS data, but will be an operational mode of the Sentinel-1 Mission, one of the key components of the Global Monitoring for Environment and Security (GMES) program [6]. The present study and the measurements executed are therefore the first in-flight antenna characterization of a SAR instrument in TOPS mode considering both: beam switching not only in range but especially in azimuth and consequently beam-to-beam gain variation in elevation and in azimuth. The study has been done using TSX experimental TOPS data.

2. Approach

For measuring the antenna pattern in TOPS mode during a pass of the satellite, so called ground receivers (GRs) are deployed and aligned in the line of sight of the SAR instrument. The DLR ground receiver detects the receive power with a logarithmic detector. The detector amplitude is digitized with an analog-to-digital converter. The digital values are stored within the GR and are read out in the laboratory after each overpass. The first step for data analysis is to transform the recorded digital samples to power expressed in dBm over a time axis. The time axis is determined by GPS time stamps, which were recorded by the ground receiver in parallel to the receive power.

Due to the flight movement of the platform, the signal recorded by the GR represents a cut through the spherical antenna pattern. Transforming from time units to antenna azimuth look angles and considering the position information of the target and the platform, the azimuth antenna pattern is obtained and can be compared to the reference pattern derived from the antenna model.

TOPS, as implemented for TSX, is a complex imaging mode which incorporates the switching of about 30 beams in azimuth (for each burst) plus the four swaths that are scanned in elevation. Thus, each received pulse must be mapped to a nominal antenna state switched on board (excitation coefficients) and consequently a correct synchronization between the orbiting instrument and the GR times is a prerequisite.

3. Measurement Set-Up and Configuration

The equipment used for measuring the TOPS azimuth patterns is a set of GRs in X-band [7]. The GRs were deployed at two test sites (D28 and D30) within the DLR calibration field located in Southern Germany, as indicated in Fig. 1.

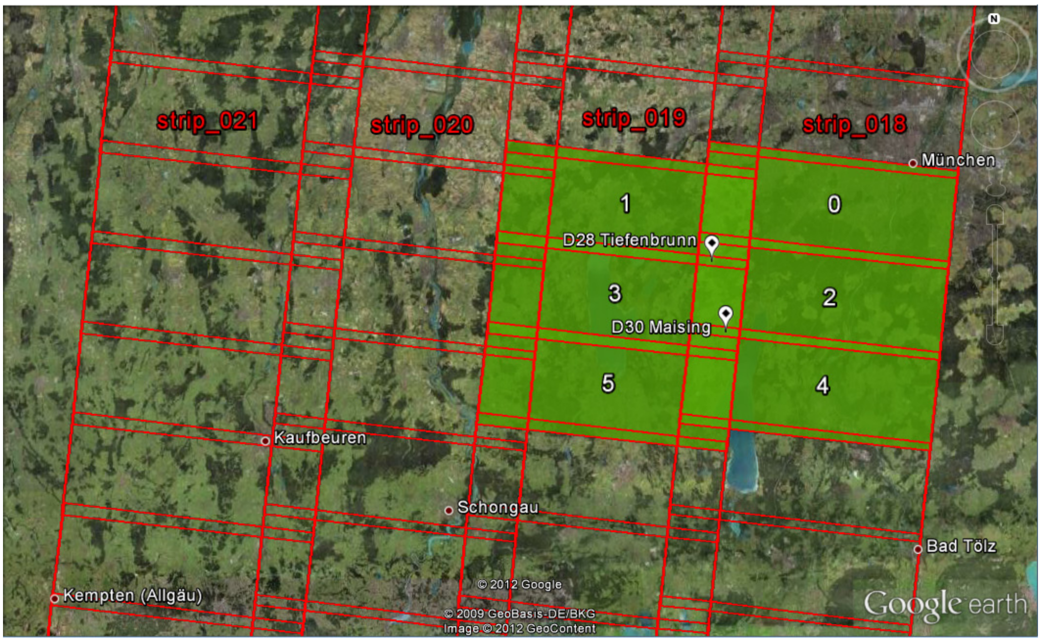

Figure 1. TSX TOPS acquisition coverage with sub-swaths and bursts indicated. Target position and burst numbering is also indicated. [© Google Earth]

Thus, not only the overlap region between two adjoining beams in range (here strip_018 and strip_019) but also the burst overlap between two steering sequences of beams in azimuth can be detected by GRs. A total of 3 GRs were installed and aligned at each of the test sites. For referring to the different bursts of interest (regions filled by green color in Figure 1) in the following analysis each burst is indicated by a number (from 0 to 5). Due to the small size of the burst overlap area, for this calibration campaign to succeed, not only the GRs had to be accurately deployed and configured, but also at instrument level the TOPS acquisition had to be precisely and reliably commanded. A total of four passes was commanded and acquired during spring 2012 for this experiment.

4. Measurement Results

Each GR records the envelope of a sequence of pulses transmitted by the satellite. Once this measurement is correctly time-labeled, the main focus then is the reconstruction of the theoretical TOPS pattern derived from information of:

- the antenna configuration on board,
- the antenna model providing the reference patterns for each switched beam (pair of azimuth/elevation pattern) and
- the geometry between the platform and the GR.

The conformity of the antenna model with the measurements is shown on Fig. 2, where it can be seen how closely the measurement and the reconstructed theoretical pattern match to each other even in the lower sidelobes. Thus, the TSX antenna model can accurately predict the beam-to-beam gain offsets not only between elevation beams but also for the azimuth beams.

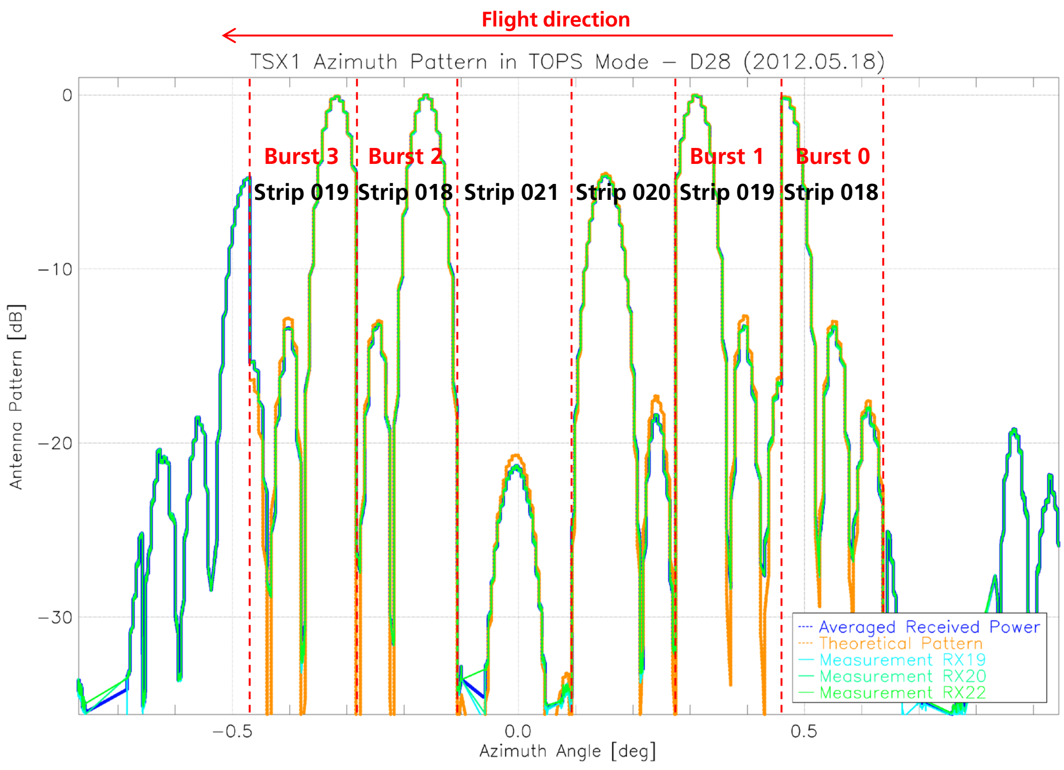

Figure 2. Comparison of the normalized TOPS azimuth pattern measured by GRs during one pass and the one reconstructed by the antenna model. Only the relevant look angles, corresponding to bursts 0-1-2-3 are shown.

Four peaks are observed, which correspond to the four neighboring bursts in the vicinity of the test site D28, where the SAR antenna is steered over the GR. The peaks correspond from right to left to bursts 0-1-2-3. In each burst the antenna is steered in the azimuth direction following a sequence of beams. As this sequence is not continuous, the antenna configuration remains a certain amount of pulses in a determinate beam, originating the staircase shape of the pattern. Sharp changes in the staircase sequence correspond to burst changes (e.g. transition from burst 0 to 1 at approximately +0.45º). Other peaks with lower amplitude correspond to other sub-swaths (strip_020 and strip_021). Furthermore, it should be

mentioned here that, just as expected, the 3 dB beamwidth appears much narrower since in TOPS the azimuth antenna pattern is compressed due to steering.
Looking closer to a single burst, the staircase shape of the pattern becomes obvious, as shown in Fig. 3. Here only burst 2 is shown, since it is one of the bursts located at the overlap region for test sites D28 and D30. Due to the different geometries, a different portion of the pattern is seen from each test site. At a given time, the backward looking beams are observable from D28, while the forward looking beams are observable from D30, i.e. while D28 is illuminated directly with the main lobe of these backward beams (main lobe in Fig. 3, left), D30 is irradiated with the sidelobe of the backward beams (sidelobes in Fig. 3, right), and when D30 is illuminated with the main lobe of the forward beams (main lobe in Fig. 3, right), then D28 is irradiated by the sidelobe of these forward beams (sidelobes in Fig. 3, left).

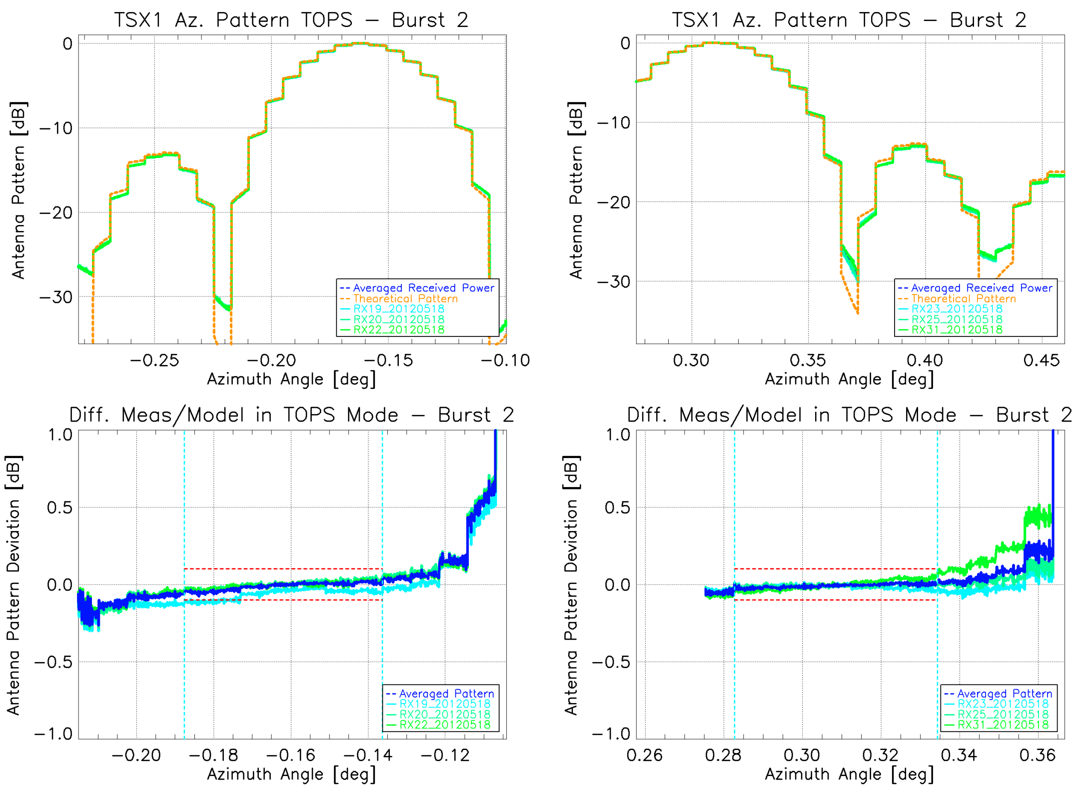

Figure 3. TOPS measurements of burst 3 on 18.05.2012: left, at test site D28; right, at test site D30.

The interesting area for the analysis is the 3 dB region of the pattern, as it is the look direction under which the target is seen by the SAR antenna. For this region, the difference between the measurement and the theoretical pattern derived by the antenna model has been calculated and is likewise shown in Fig. 3 (left and right, below). Since each GR has slightly different characteristics, the measurements of 3 GRs deployed at one test side are combined to obtain an averaged measurement pattern. The diagrams show that the deviation is kept between ±0.1 dB along the 3 dB region of the azimuth patterns and this for different beams as well as for different azimuth look angles (corresponding to the different bursts and sites).
These results are remarkable since they demonstrate that the antenna model can predict the shape of the antenna pattern with extreme precision even for such a complex imaging mode as TOPS. Hence, the antenna model of TerraSAR-X fulfills the strong requirements of ±0.1 dB for one-way azimuth antenna patterns also for the experimental TOPS mode, after 5 years of mission time.
In Fig. 4 (left) the difference between the measurement and the antenna model is shown for the 3 dB region of the pattern (for each of the analyzed six bursts). The measurements are

again averaged over the three deployed GRs per test site and pass. The statistic information is presented by the vertical bars on the left of the diagrams. The ends of a bar represent the minimum and the maximum, the star is the mean deviation and the triangles are the standard deviation. For this specific pattern measurement, the deviation is higher than ±0.1 dB. However, the deviation decreases when the pattern derived from the antenna model is shifted barely about 0.005 degrees, as indicated in Fig. 4 (right). This is observed for both test sites (each test site has a different color: D28 is blue, D30 is yellow), which means that for different geometries between the satellite and the test site, the same "mispointing" could be determined and consequently be corrected for.

This marginal mispointing is in the order of a few millidegrees and consequently in the order of the attitude accuracy of TerraSAR-X, which was verified in 2007 [6]. The mispointing does not always appear and changes from one pass to another, but stays rather constant during one pass. For example, the measurement on 2012-05-18 presents a very low deviation value even for the uncorrected case, as it is shown on Fig. 5.

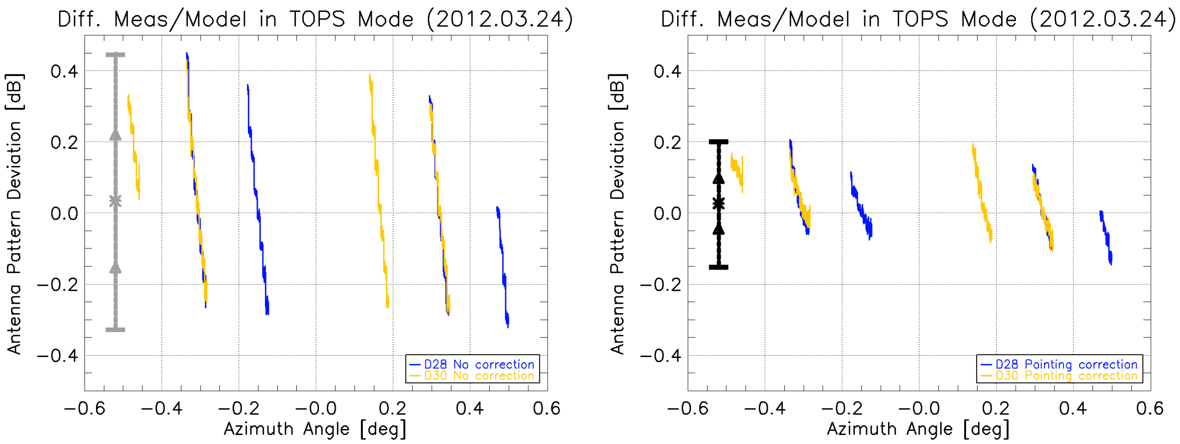

Figure 4. Difference between measurement on March 24th 2012 and model for the 3 dB region of the TOPS azimuth patterns, statistical values: grey/black. Left: without pointing correction, right: with pointing correction.

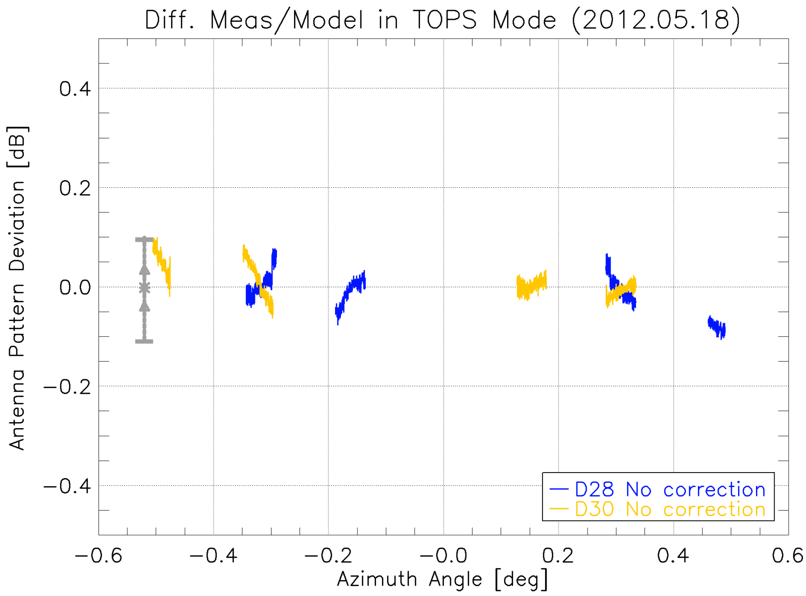

Figure 5. Difference between measurement on May 18th 2012 and model for the 3 dB region of the TOPS azimuth patterns, statistical values: grey/black. No pointing correction was needed for this data set.

To sum up, applying the pointing correction described before, the difference between measurement and model, including the minima and the maxima, is less than ±0.2 dB. Thus, the described approach for characterizing the azimuth antenna pattern in TOPS mode is also well suitable for deriving the actual pointing in the azimuth direction of the SAR instrument.

5. Conclusions

The method for azimuth antenna pattern verification based on ground receiver measurements was tried for the case of the TerraSAR-X instrument operating in TOPS mode during 4 passes/4 acquisitions at two different test sites with 3 GRs per test site. The results show that for reconstructing the azimuth pattern by means of the antenna model, the geometry between the satellite and the GR position on the Earth's surface as well as the beam configurations, the deviation between the measured azimuth patterns and the theoretical patterns is in the order of two tenths of a dB.

Compensating furthermore a slight mispointing arisen from a finite attitude knowledge, an accuracy of the antenna model of better than ±0.15 dB has been achieved for the experimental TOPS mode of TerraSAR-X. The accuracy includes both the shape within the main beam and the gain-offset between different beams. This accuracy is similar to that demonstrated for all operational modes, even as the satellite reaches its nominal end-of-life.

The current analysis was done pulse to pulse: it is not relevant for the algorithm how many beams were used during the acquisition. The most important thing is to know the right antenna configuration at each time and the correct synchronization of the data. Therefore this calibration method is suitable for other satellite missions such as Sentinel-1 that will use the TOPS as an operational mode. However, the complexity may increase if the amount of steered beams is higher.

Finally, the method based on GRs and proposed for measuring the azimuth pattern of a SAR system in the complex TOPS mode is well suitable for: verifying the correct operation of the instrument in TOPS mode, measuring the azimuth pattern even in swath and burst overlap regions, verifying the antenna model, and deriving a residual mispointing.

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